# D-C AMPLIFIERS USING TRANSISTORS

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## I. INTRODUCTION

Improving d-c transistor amplifiers is very difficult because the parameters of current gain, base-emitter voltage and collector-base leakage current have a high degree of temperature sensitivity.

It is the purpose of this paper to review some of the methods used to obtain low-drift amplifiers, both chopper and conventional types, and to indicate the performance which is possible with a given complexity.

A compromise amplifier is presented which is moderately simple and whose performance, while not the best available, is nevertheless more than adequate for most applications.

## II. REVIEW OF D-C AMPLIFIER TYPES

A widely used method of drift elimination is by the use of a chopper amplifier (Ref. 1) in which the d-c voltage is converted to a-c, amplified in an a-c and therefore low-drift amplifier and then converted back to d-c.

However, the disadvantages include the use of a mechanical chopper with its high power consumption, noise generation and sometimes questionable reliability, a very-low-frequency response of the order of tens of cycles per second and circuit complexity. Some of these disadvantages can be removed by the use of a semiconductor chopper, but at present, these are generally unsatisfactory due to the turn-on and turn-off voltage transients and the temperature sensitive offset voltage. Certain improvements in semiconductor technology under investigation promise to greatly reduce these problems, but those of circuit complexity and others remain.

A second and more versatile method is to use a chopper stabilized arrangement first presented by Goldberg (Ref. 2) and, in a form more suitable for transistors, by Blecher (Ref. 3) and by Okada (Ref. 4). In this arrangement, the drift is chopped, a-c amplified, smoothed and re-applied to the input such as to compensate for the output drift. This has proved to be an exceedingly useful method and, again, has been widely used.

However, the disadvantages are the same as the other system except for the frequency restriction, more circuit complexity, and instability problems.

The instability problem has been studied both for high-impedance and low-impedance amplifiers by Bénéteau, Blaser and Lane (Ref. 5) and criteria have been developed for stable operation which is sometimes difficult to achieve in a practical wide-band amplifier.

The third and simplest method is to use a straight d-c amplifier, which, while considerably more attractive from a complexity point of view, is usually of a very much lower order of performance as compared to the chopper types. The main parameters responsible for this inferior performance are the variation of $V_{BE}$, $h_{FE}$ and $I_{CBO}$ with temperature.

Nevertheless, certain improvements in transistor technology have been made by Fairchild Semiconductor with the introduction of planar transistors in which the effect of two of these parameters, $I_{CBO}$ and $V_{BE}$, have been greatly reduced.

Another important improvement has been the mounting of two transistors on one header to minimize the temperature difference and thus the parameter variation between two transistors in a

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differential pair. These transistors are presently available commercially.

Using these improvements, performance nearly equal to the chopper types can be obtained with sophisticated straight d-c amplifiers (Ref. 6, 7), while less adequate performance can be achieved by simpler amplifiers of the conventional Slaughter type (Ref. 7, 8).

## III. CONVENTIONAL DIFFERENTIAL AMPLIFIER

A conventional differential amplifier is shown in Fig. 1. It can be shown that the output voltage, $e_0$, is given by

$$e_0 = A\left[\left(V_{BE_2} - V_{BE_1}\right) + \left(e_1 - e_2\right) + \left(I_{CBO_2} - I_{CBO_1}\right) R_S + \left(h_{FE_1} - h_{FE_2}\right) \cdot \left(V_{EE} - V_{BE_1} - e_1\right)\left(\frac{R_S}{2R_E h_{FE_1} h_{FE_2}}\right) + \left(1 - 2K\right)\left(V_{EE} - V_{BE_1} + e_1\right)\frac{R_2}{2R_E}\right]$$

where

$$A = \frac{2R_L}{R_2 + R_S\left(\frac{1}{h_{FE_1}} + \frac{1}{h_{FE_2}}\right)}$$

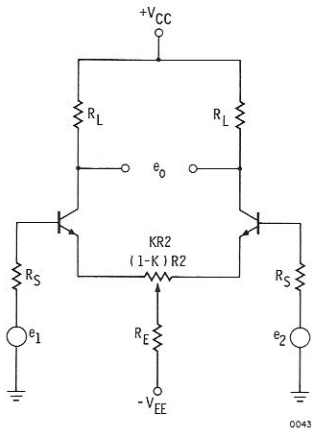



**FIG. 1.** A conventional differential amplifier.

From the above equation, it can be seen that the output is zero only for equal inputs of $V_{BE}$, $I_{CBO}$ and $h_{FE}$. Generally, in most planar transistors, $I_{CBO}$ is negligibly small and $V_{BE}$ tracking between two transistors is very much better than with other types of devices. However, the difference in $h_{FE}$ remains, and the performance of the Slaughter amplifier can be improved only up to a point.

The improvement is quite marked, however, and for source impedances of the order of one kilohm, drifts of the order of 30 $\mu$V/°C, referred to the input, can be obtained with unselected transistors.

This is several times better than could previously be reliably obtained with other unselected types.

## IV. A MORE SOPHISTICATED DIFFERENTIAL AMPLIFIER

Considerable improvement can be obtained by the use of NPN-PNP pairs, as in Figs. 2 and 3. A practical circuit as in Fig. 2 described in Ref. 7 has drifts of the order of 10 $\mu$V/°C for one-kilohm source impedances.

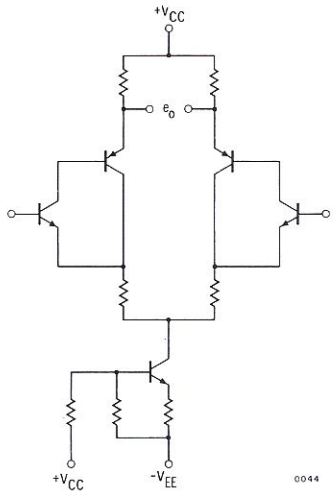



**FIG. 2.** An improved differential amplifier.

The added circuitry of Fig. 3 results from the requirement that, for low drift, the operating points of the differential transistors must remain as closely alike as possible.

A practical circuit as in Fig. 3 has drifts of the order of 3 to 5 $\mu$V/°C. The Zener diodes are used to match the $V_{BE}$ characteristic of the PNP transistors in order to get constant collector-emitter voltage on the drift-determining NPN's.

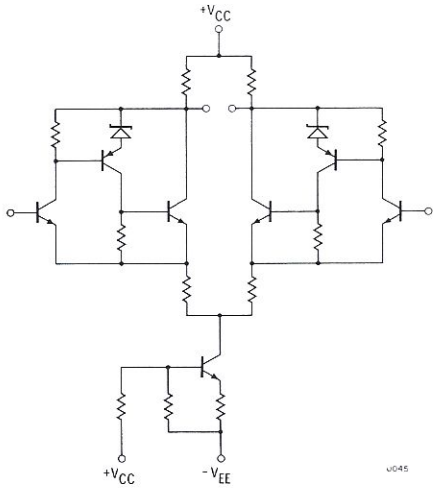



**FIG. 3.** Improved differential amplifier with additional stabilization.

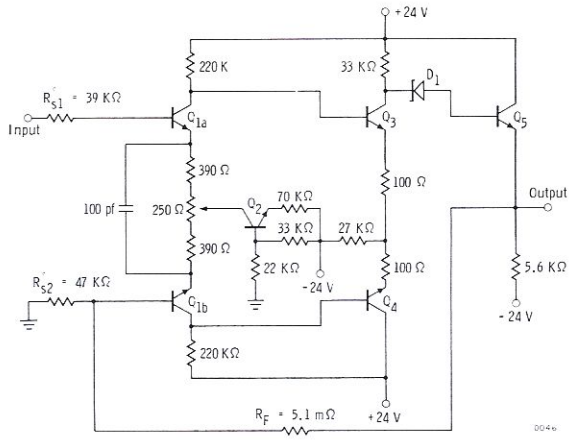
For high impedance applications, however, the chopper types remain much better due to their ability to compensate for the voltage drop in the base-feeding resistor. Certain techniques are possible to compensate this voltage in a straight d-c amplifier, but temperature compensation is then difficult.

## V. A PRACTICAL AMPLIFIER

The performance of these amplifiers is very much better than previously attainable, but is at the expense of circuit complexity. Furthermore, the input impedance usually required is more than the 1000 ohms used.

For this reason, a simple amplifier was constructed and tested which has the relatively high input impedance of several hundred kilohms, a gain of 100 and a drift of the order of 20 $\mu$V/°C.

The amplifier schematic is shown in Fig. 4.




| | |
|---|---|
| $Q_{1A}$, $Q_{1B}$ | FSP 30 |
| $Q_3$, $Q_4$ | 2N1711 |
| $Q_2$, $Q_5$ | 2N1613 |
| $D_1$ | EB Junction of 2N1613 |

The FSP 30 can be replaced by 2-2N1711's but with reduced performance * See text

**FIG. 4.** A practical d-c amplifier.

The input and second stages consist of conventional differential pairs with a constant current source in the emitter of $Q_1$.

The output emitter follower is fed through a Zener diode in order to have the output at ground level permitting feedback to the base of $Q_{1b}$.

The Zener diode used is a 2N1613 transistor with an emitter-base reverse-biased junction. Its characteristic is very sharp at very low currents, unlike most Zeners, and furthermore compensates for the negative $V_{BE}$ characteristic of the emitter follower. The negative feedback primarily raises the input impedance and also stabilizes the gain and reduces the output impedance.

The a-c stability of the amplifier was not calculated, and, for a production amplifier, the analysis should be done according to the methods of Ref. 5.

The performance of the amplifier is indicated in Fig. 5(a) and (b). Drifts of the order of 12 $\mu$V/°C have been observed (referred to the input) for $R_{S_1}$ equals 39,000 and $R_{S_2}$ equals 47,000.

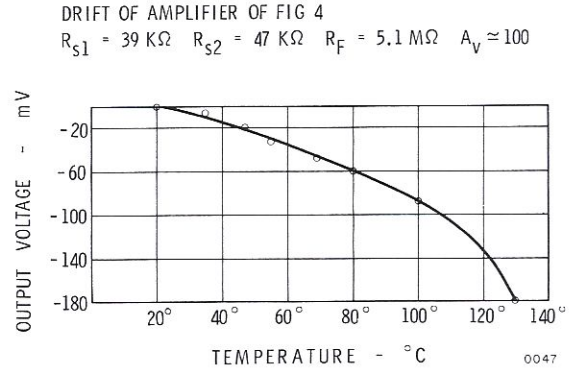



**FIG. 5a.** Measured drift of amplifier with temperature.

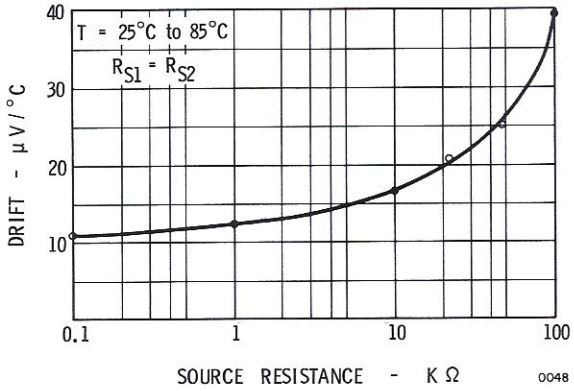



**FIG. 5b.** Measured drift of amplifier with source resistance.

It was observed that the drift was appreciably reduced by making the source resistances not exactly alike but different by a factor $R_{S_1} : R_{S_2}$ of 0.85 : 1; this behavior is not understood. Drift referred to the input is shown in Fig. 5(b).

The dynamic range of the amplifier is about ±9 volts and is shown in Fig. 6.

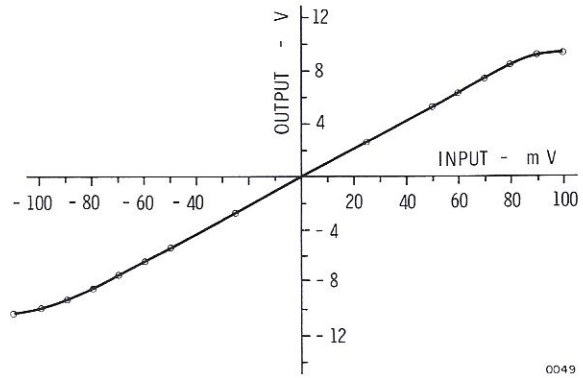



**FIG. 6.** Dynamic range of amplifier.

## VI. CONCLUSION

New planar semiconductors and circuit techniques now permit the construction of straight d-c amplifiers of the same order of performance as the chopper type amplifiers for low impedance applications, although the latter remain better for high-impedance applications.

## ACKNOWLEDGEMENT

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